

Analysis of a System
is composed of
numerous components

Fundamental
Laws

Mathematics
(Calculus)

1st Law
(Energy Conservation)
2nd Law
(Entropy)
Mass Conservation

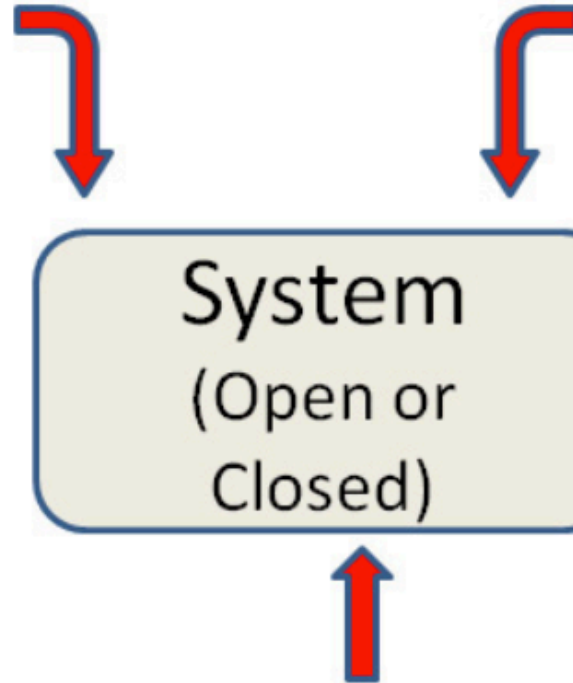
System
(Open or
Closed)

Properties

P, T, E, v, h, s
Eqns of State
Tables

Process

iso = constant
Isobaric
Isothermal
Isochoric = Constant Volume !



Kinetic Energy for a mass (m) at a velocity (V) (an Extensive Property)

$$KE = \frac{1}{2} m V^2$$

Frequently, one is interested in the change of KE from State 1 to State 2:

$$\Delta KE = \frac{1}{2} m (V_2^2 - V_1^2)$$

Potential Energy for a mass (m) in a gravitational potential field (g) at a height z (an Extensive Property)

$$PE = m g z$$

Frequently, one is interested in the change of PE from State 1 to State 2:

$$\Delta PE = PE_2 - PE_1 = m g (z_2 - z_1)$$

Internal Energy (U): A measure of energy at a macroscopic level due to the molecular translation, vibration, rotation (an Extensive Property).

Internal Energy (u) can also be expressed as an intensive property $u=U/m$ (internal energy per unit mass).

U (u) is more difficult to measure, compared to velocity and or height/elevation. Hence, they are usually tabulated in tables – Thermodynamic Tables.

Single-Phase Regions

► **Example:** Properties associated with **superheated water vapor** at **10 MPa** and **400°C** are found in **Table A-4**.

► $v = 0.02641 \text{ m}^3/\text{kg}$

► $h = 3096.5 \text{ kJ/kg}$

► $u = 2832.4 \text{ kJ/kg}$

► $s = 6.2120 \text{ kJ/kg}\cdot\text{K}$

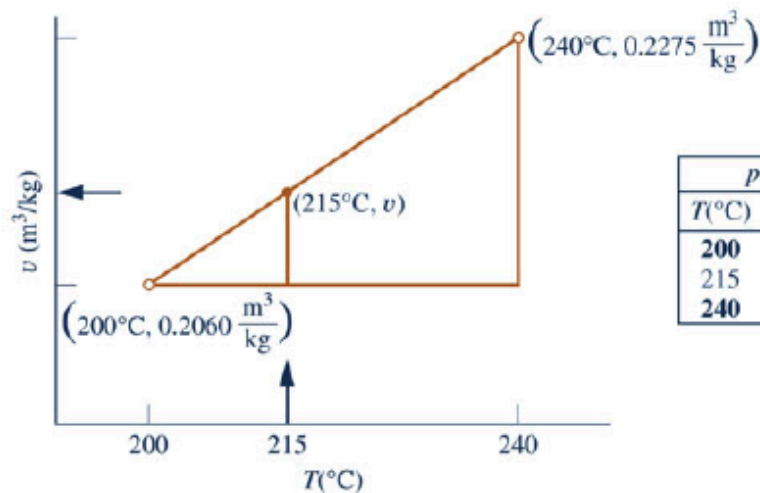
Table A-4

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg·K
$p = 80 \text{ bar} = 8.0 \text{ MPa}$ ($T_{\text{sat}} = 295.06^\circ\text{C}$)					$p = 100 \text{ bar} = 10.0 \text{ MPa}$ ($T_{\text{sat}} = 311.06^\circ\text{C}$)			
Sat.	0.02352	2569.8	2758.0	5.7432	0.01803	2544.4	2724.7	5.6141
320	0.02682	2662.7	2877.2	5.9489	0.01925	2588.8	2781.3	5.7103
360	0.03089	2772.7	3019.8	6.1819	0.02331	2729.1	2962.1	6.0060
400	0.03432	2863.8	3138.3	6.3634	0.02641	2832.4	3096.5	6.2120
440	0.03742	2946.7	3246.1	6.5190	0.02911	2922.1	3213.2	6.3805
480	0.04034	3025.7	3348.4	6.6586	0.03160	3005.4	3321.4	6.5282

Linear Interpolation

- ▶ When a state does not fall exactly on the grid of values provided by property tables, **linear interpolation** between adjacent entries is used.
- ▶ **Example:** Specific volume (v) associated with **superheated water vapor** at **10 bar** and **215°C** is found by **linear interpolation** between adjacent entries in **Table A-4**.

$$\text{slope} = \frac{(0.2275 - 0.2060) \text{ m}^3/\text{kg}}{(240 - 200)^\circ\text{C}} = \frac{(v - 0.2060) \text{ m}^3/\text{kg}}{(215 - 200)^\circ\text{C}} \rightarrow v = 0.2141 \text{ m}^3/\text{kg}$$



$p = 10 \text{ bar}$	
T ($^\circ\text{C}$)	v (m^3/kg)
200	0.2060
215	$v = ?$
240	0.2275

Table A-4

T $^\circ\text{C}$	v m^3/kg	u kJ/kg	h kJ/kg	s $\text{kJ/kg}\cdot\text{K}$
$p = 10 \text{ bar} = 1.0 \text{ MPa}$ ($T_{\text{sat}} = 179.91^\circ\text{C}$)				
Sat.	0.1944	2583.6	2778.1	6.5865
200	0.2060	2621.9	2827.9	6.6940
240	0.2275	2692.9	2920.4	6.8817

Two-Phase Liquid-Vapor Region

► **Tables A-2/A-2E**
(Temperature Table) and
A-3/A-3E (Pressure Table)
provide

- saturated liquid (f) data
- saturated vapor (g) data

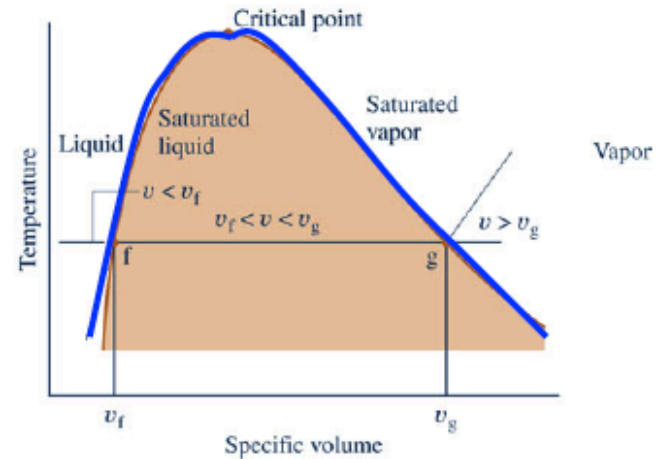


Table note: For saturated liquid specific volume, the table heading is $v_f \times 10^3$.
At 8°C, $v_f \times 10^3 = 1.002 \rightarrow v_f = 1.002/10^3 = 1.002 \times 10^{-3}$.

Table A-2		Specific Volume m ³ /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg-K		Temp °C
Temp °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8

Internal Energy and Enthalpy of Ideal Gases

- ▶ For a gas obeying the **ideal gas model**, **specific internal energy depends only on temperature**. Hence, the specific heat c_v , defined by **Eq. 3.8**, is also a function of temperature alone. That is,

$$c_v(T) = \frac{du}{dT} \quad (\text{ideal gas}) \quad \text{(Eq. 3.38)}$$

- ▶ On integration,

$$u(T_2) - u(T_1) = \int_{T_1}^{T_2} c_v(T) dT \quad (\text{ideal gas}) \quad \text{(Eq. 3.40)}$$

Internal Energy and Enthalpy of Ideal Gases

- ▶ Similarly, for a gas obeying the **ideal gas model**, **specific enthalpy depends only on temperature**. Hence, the specific heat c_p , defined by **Eq. 3.9**, is also a function of temperature alone. That is,

$$c_p(T) = \frac{dh}{dT} \quad (\text{ideal gas}) \quad \text{(Eq. 3.41)}$$

- ▶ On integration,

$$h(T_2) - h(T_1) = \int_{T_1}^{T_2} c_p(T) dT \quad (\text{ideal gas}) \quad \text{(Eq. 3.43)}$$

Internal Energy and Enthalpy of Ideal Gases

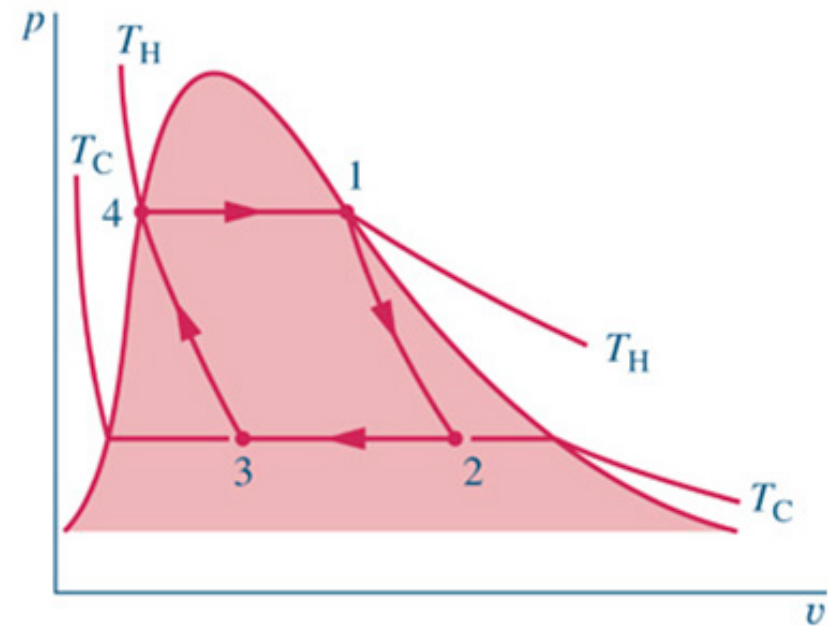
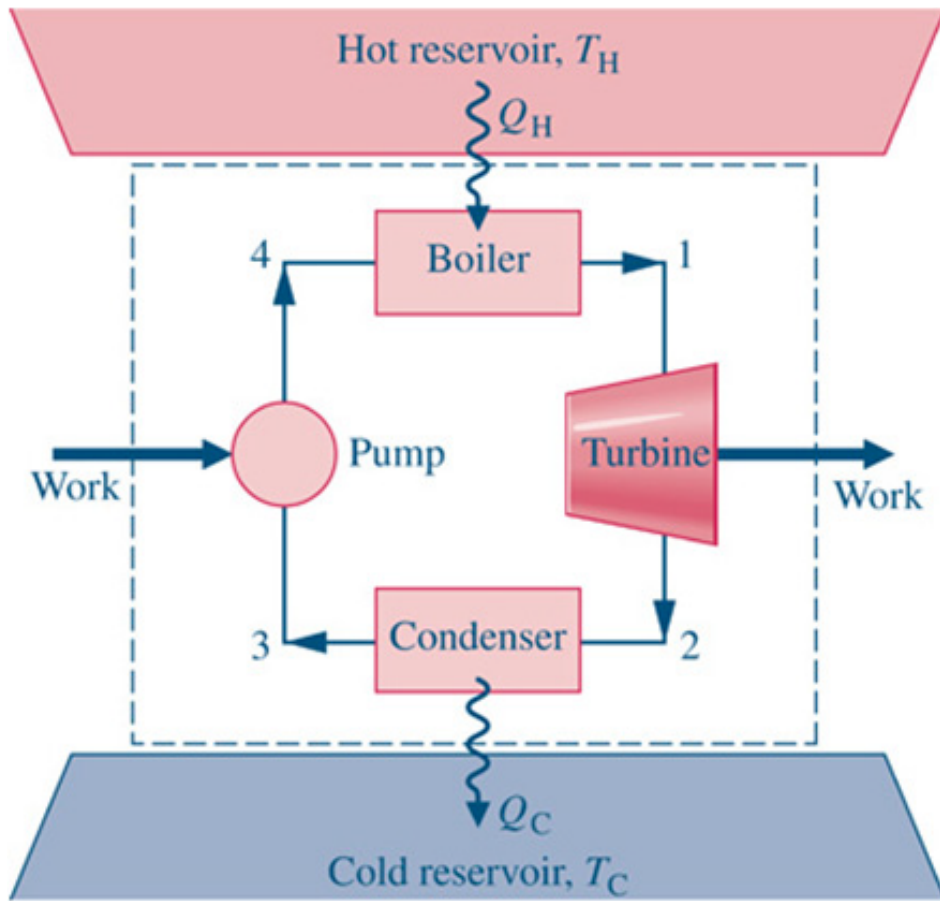
- ▶ In applications where the specific heats are modeled as constant,

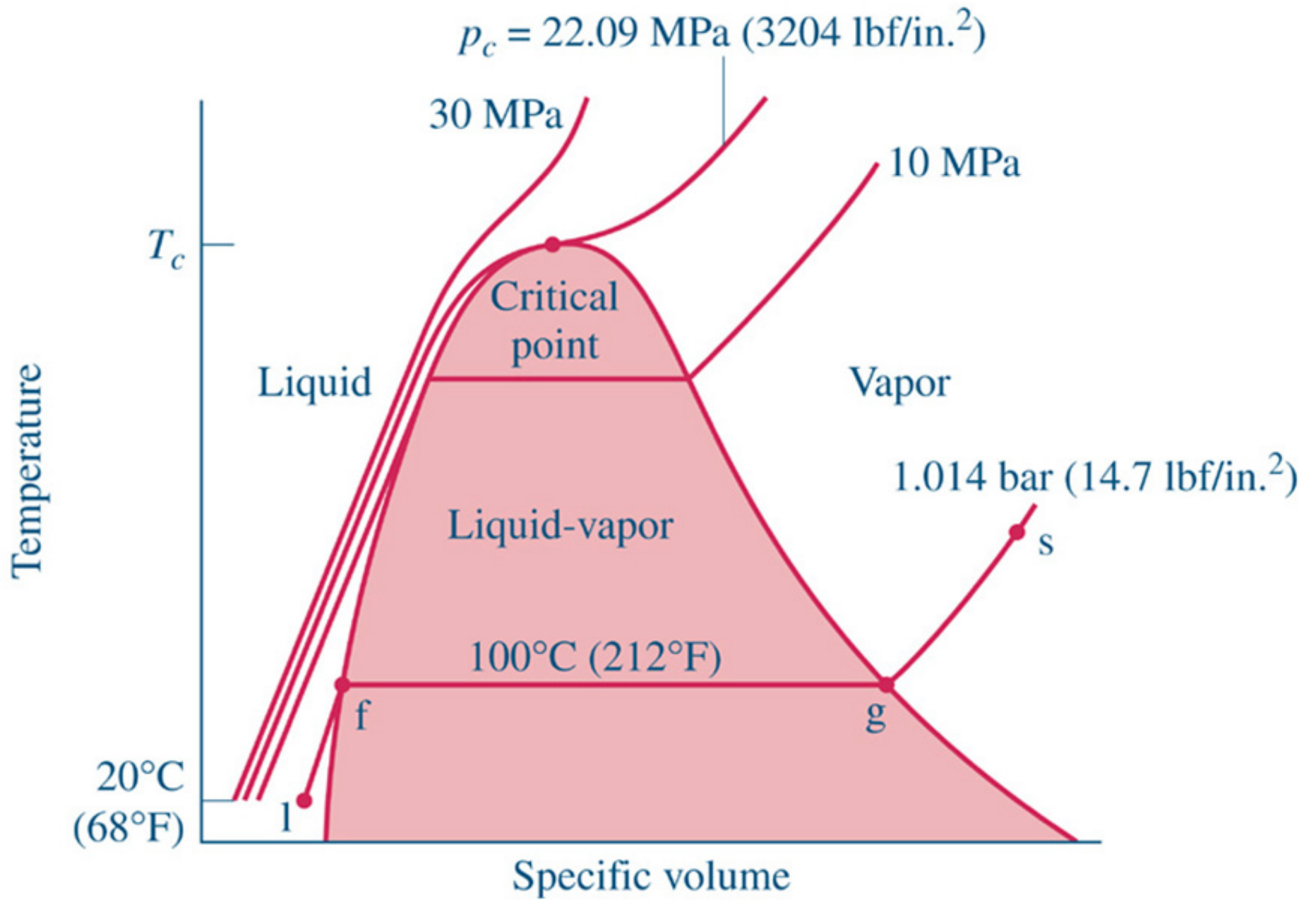
$$u(T_2) - u(T_1) = c_v [T_2 - T_1] \quad (\text{Eq. 3.50})$$

$$h(T_2) - h(T_1) = c_p [T_2 - T_1] \quad (\text{Eq. 3.51})$$

- ▶ For several common gases, evaluation of changes in specific internal energy and enthalpy is facilitated by use of the *ideal gas tables*:
Tables A-22 and **A-23**.
- ▶ **Table A-22** applies to air modeled as an ideal gas.

Cycles





First Law of Thermodynamics for a Control Volume

$$\frac{dE}{dt} = \dot{Q}_{cv} - \dot{W} + \dot{m} \left[(u_{in} - u_{out}) + \frac{(V_{in}^2 - V_{out}^2)}{2} + g(z_{in} - z_{out}) \right]$$

$$h = u + Pv$$

$$\frac{dE}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m} \left[(h_{in} - h_{out}) + \frac{(V_{in}^2 - V_{out}^2)}{2} + g(z_{in} - z_{out}) \right]$$

Energy Transfer by Heat

- ▶ The symbol Q denotes an **amount of energy transferred** across the boundary of a system **by heat transfer**.
- ▶ **Heat transfer into a system** is taken as **positive** and **heat transfer from a system** is taken as **negative**:
 - ▶ $Q > 0$: heat transfer **to the** system
 - ▶ $Q < 0$: heat transfer **from** the system

The same sign convention is used for the **rate of energy transfer by heat**, denoted by \dot{Q} .

- ▶ If a system undergoes a process involving **no heat transfer** with its surroundings, that process is called **adiabatic**.

Energy Transfer by Work

- ▶ The symbol W denotes an **amount of energy transferred** across the boundary of a system **by work**.
- ▶ Since engineering thermodynamics is often concerned with internal combustion engines, turbines, and electric generators whose purpose is to do work, **it is convenient to regard the work done by a system as positive**.
 - ▶ $W > 0$: work **done by** the system
 - ▶ $W < 0$: work **done on** the system

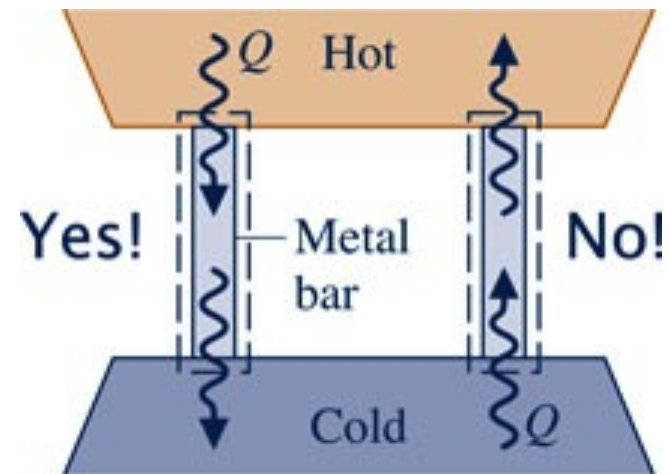
The same sign convention is used for the **rate of energy transfer by work (power!)**, denoted by \dot{W} .

Second Law of Thermodynamics

Alternative statements of the second law,

Clausius Statement of the Second Law

It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body.

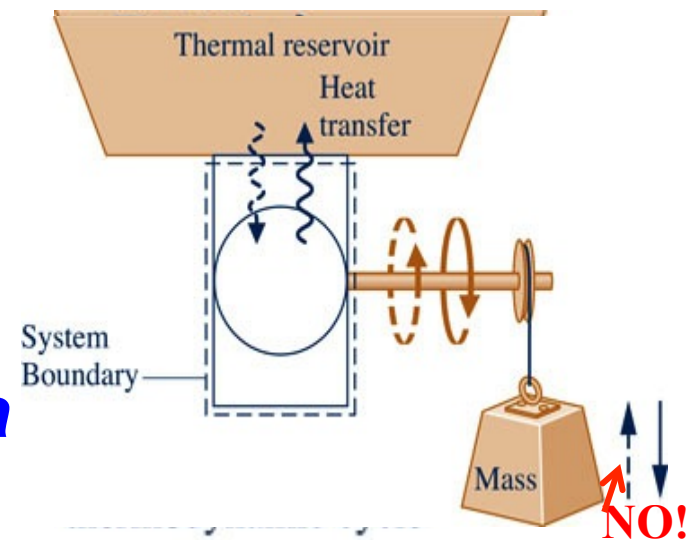


Second Law of Thermodynamics

Alternative statements of the second law,

Kelvin-Planck Statement of the Second Law

It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir.



Aspects of the Second Law of Thermodynamics

- ▶ From conservation of mass and energy principles, (i.e. 1st Law of Thermodynamics)
 - ▶ mass and energy cannot be created or destroyed.
- ▶ For a process, conservation of mass and energy principles indicate the disposition of mass and energy but do not infer whether the process can actually occur.
- ▶ The second law of thermodynamics provides the guiding principle for whether a process can occur.

THEIR QUEST LED THEM TO A TERRIFYING DISCOVERY

The First AND Second LAWS

A CARTOON INTRODUCTION TO CLASSICAL THERMODYNAMICS

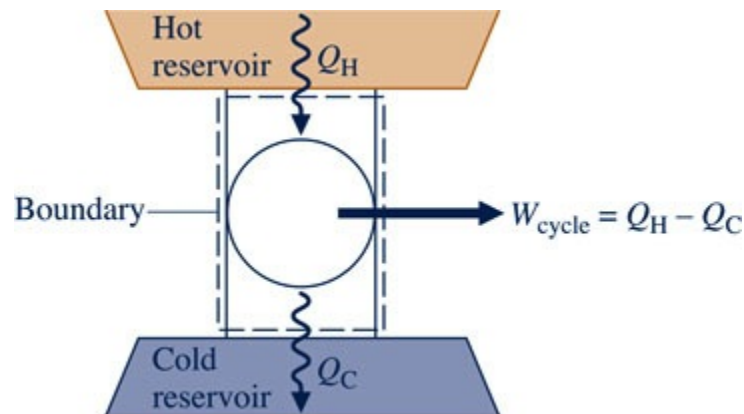
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OVER 150 FIGURES



Applications to Power Cycles Interacting with *Two* Thermal Reservoirs

For a system undergoing a **power cycle** while **communicating thermally with *two* thermal reservoirs**, a hot reservoir and a cold reservoir, **the thermal efficiency of any such cycle is**

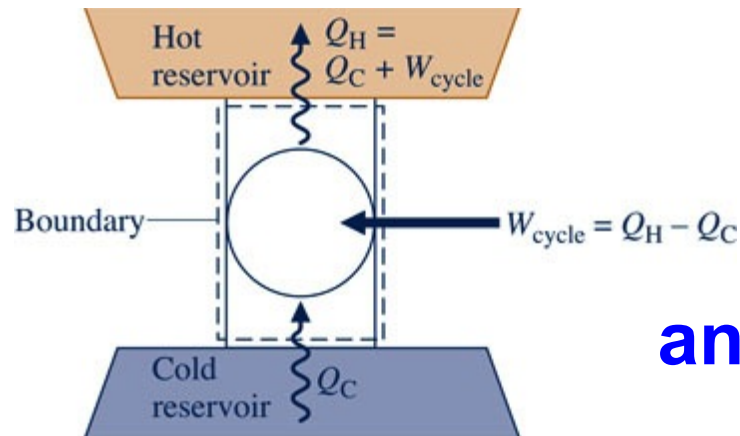


$$\eta = \frac{W_{\text{cycle}}}{Q_H} = 1 - \frac{Q_C}{Q_H} \quad \text{(Eq. 5.4)}$$

Applications to Refrigeration and Heat Pump Cycles Interacting with Two Thermal Reservoirs

For a system undergoing a **refrigeration cycle** or **heat pump cycle** while **communicating thermally with two thermal reservoirs**, a hot reservoir and a cold reservoir,

the coefficient of performance for the refrigeration cycle is



$$\beta = \frac{Q_C}{W_{\text{cycle}}} = \frac{Q_C}{Q_H - Q_C} \quad \text{(Eq. 5.5)}$$

and for the heat pump cycle is

$$\gamma = \frac{Q_H}{W_{\text{cycle}}} = \frac{Q_H}{Q_H - Q_C} \quad \text{(Eq. 5.6)}$$

Maximum Performance Measures for Cycles Operating between Two Thermal Reservoirs

It follows that the **maximum theoretical** thermal efficiency and coefficients of performance in these cases are **achieved only by reversible cycles**. Using Eq. 5.7 in Eqs. 5.4, 5.5, and 5.6, we get respectively:

Power Cycle:

$$\eta_{\max} = 1 - \frac{T_C}{T_H} \quad \text{(Eq. 5.9)}$$

Refrigeration Cycle:

$$\beta_{\max} = \frac{T_C}{T_H - T_C} \quad \text{(Eq. 5.10)}$$

Heat Pump Cycle:

$$\gamma_{\max} = \frac{T_H}{T_H - T_C} \quad \text{(Eq. 5.11)}$$

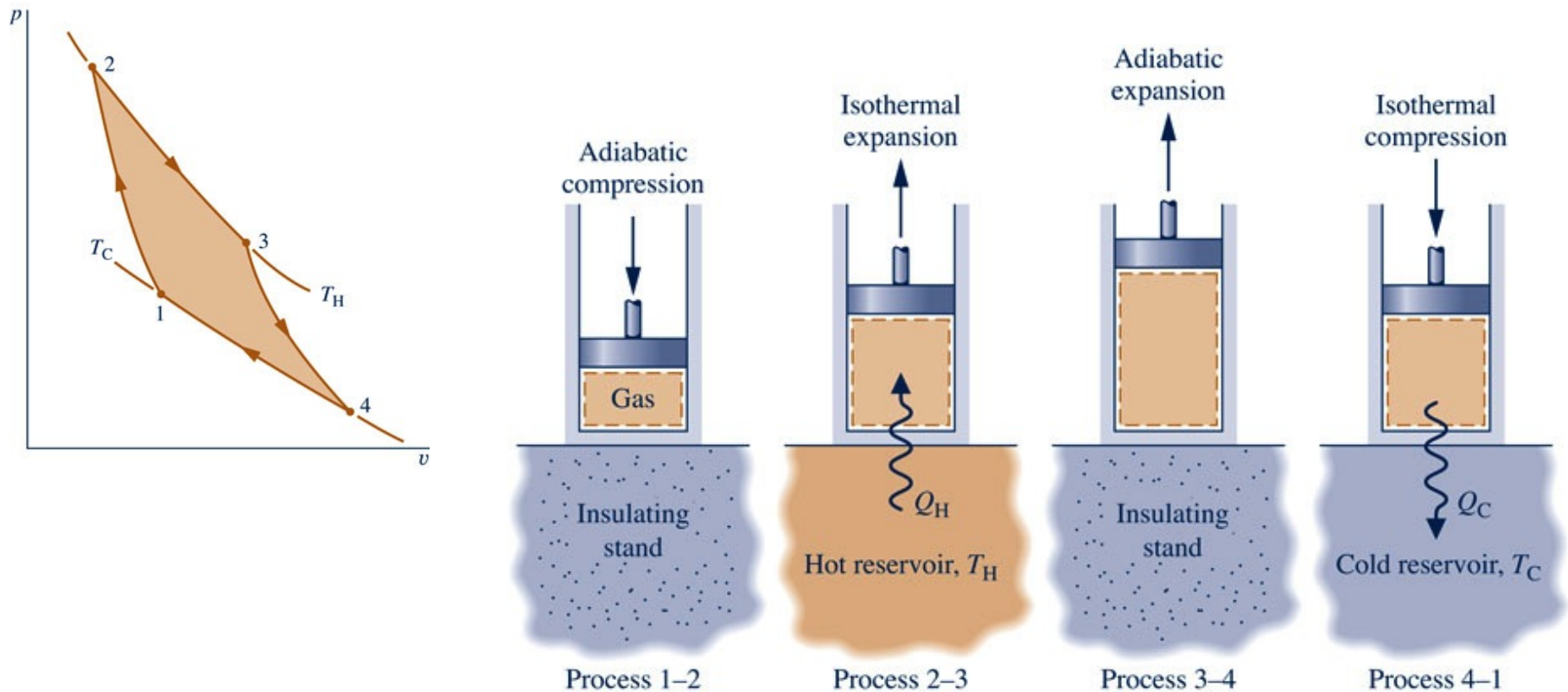
where T_H and T_C must be on the **Kelvin** or **Rankine scale**.

Carnot Cycle

- ▶ The **Carnot cycle** provides a specific example of a **reversible cycle that operates between two thermal reservoirs**. Other examples are provided in Chapter 9: the Ericsson and Stirling cycles.
- ▶ In a **Carnot cycle**, the system executing the cycle undergoes a series of **four internally reversible processes: two adiabatic processes alternated with two isothermal processes**.

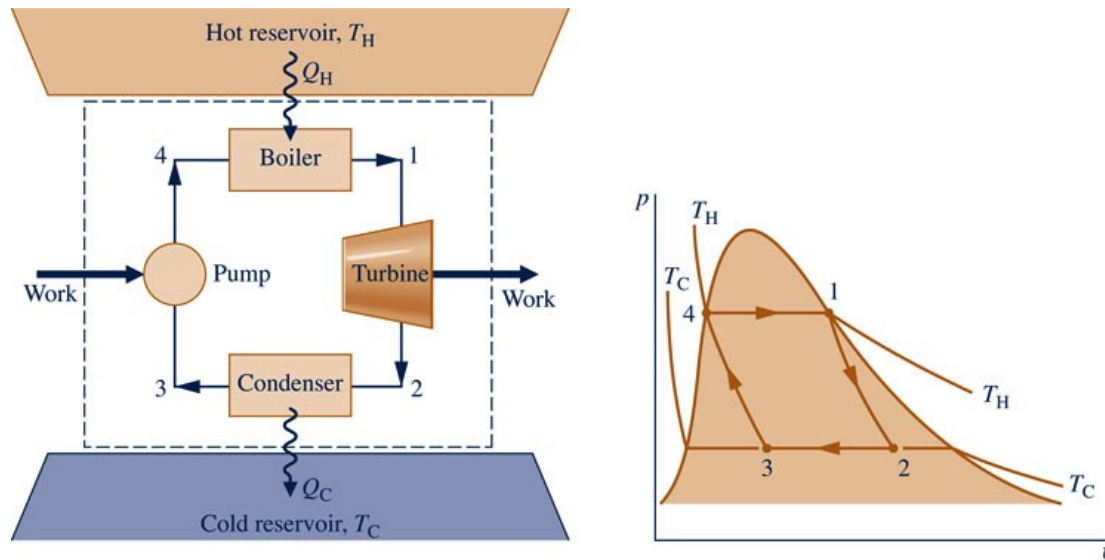
Carnot Power Cycles

The p - v diagram and schematic of a gas in a piston-cylinder assembly executing a Carnot cycle are shown below:



Carnot Power Cycles

The p - v diagram and schematic of water executing a Carnot cycle through four interconnected components are shown below:



In each of these cases the thermal efficiency is given by

$$\eta_{\max} = 1 - \frac{T_C}{T_H}$$

(Eq. 5.9)

Entropy and Heat Transfer

- ▶ In an internally reversible, adiabatic process (no heat transfer), entropy remains constant. Such a **constant-entropy process** is called an ***isentropic*** process.
- ▶ On rearrangement, **Eq. 6.2b** gives

$$(\delta Q)_{\text{int rev}} = T dS$$

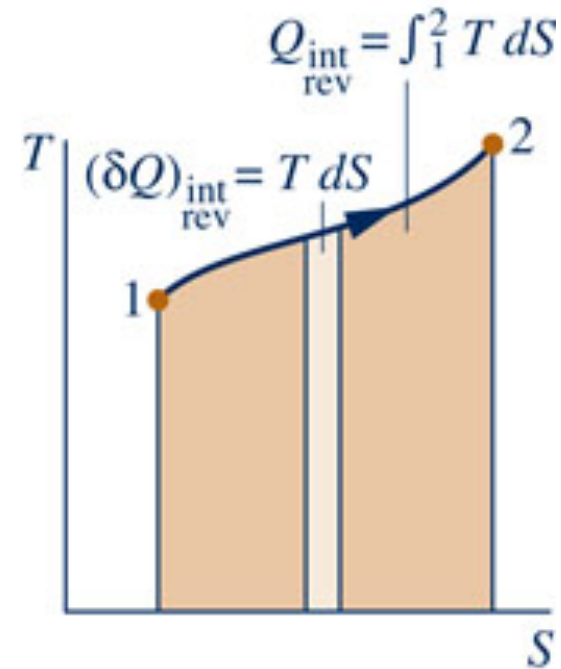
Integrating from state 1 to state 2,

$$Q_{\text{int rev}} = \int_1^2 T dS$$

(Eq. 6.23)

Entropy and Heat Transfer

From this it follows that an **energy transfer by heat to a closed system** during an internally reversible process is **represented by an area on a temperature-entropy diagram**:



Modeling Expansion and Compression Work

▶ From mechanics, the work done by the gas as the piston face moves from x_1 to x_2 is given by

$$W = \int F dx = \int p A dx$$

▶ Since the product $A dx = dV$, where V is the volume of the gas, this becomes

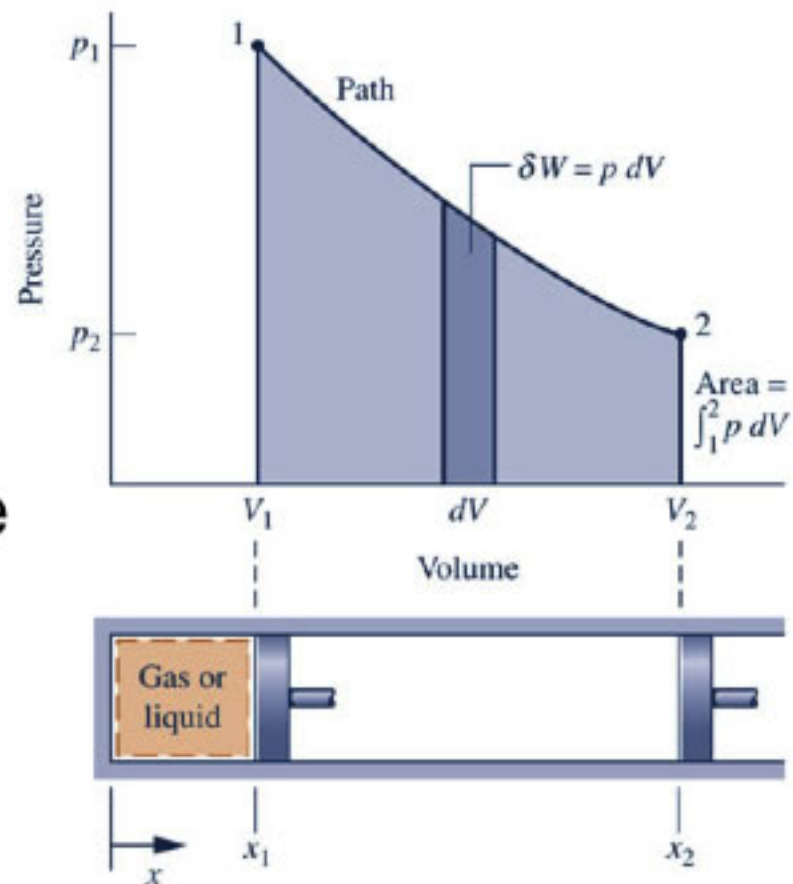
$$W = \int_{V_1}^{V_2} p dV \quad \text{(Eq. 2.17)}$$

▶ For a **compression**, dV is **negative** and so is the value of the integral, in keeping with the sign convention for work.

Modeling Expansion and Compression Work

► In a quasiequilibrium expansion, the gas moves along a **pressure-volume curve**, or path, as shown.

► Applying **Eq. 2.17**, the **work done by the gas** on the piston is given by the **area under the curve of pressure versus volume**.



Entropy Rate Balance for Control Volumes

- ▶ Like mass and energy, **entropy can be transferred into or out of a control volume by streams of matter.**
- ▶ Since this is the principal difference between the closed system and control volume entropy rate balances, the **control volume form** can be obtained by modifying the closed system form to **account for such entropy transfer.** The result is

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv}$$

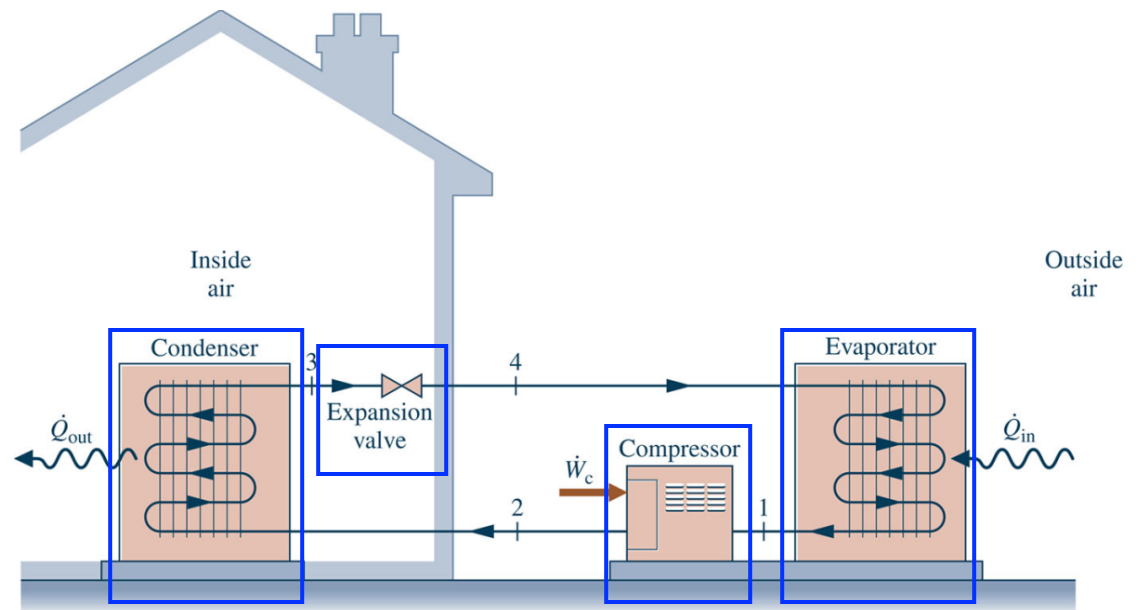
rate of entropy change		rates of entropy transfer		rate of entropy production
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(Eq. 6.34)

where $\dot{m}_i s_i$ and $\dot{m}_e s_e$ **account, respectively, for rates of entropy transfer accompanying mass flow at inlets i and exits e .**

Vapor-Compression Heat Pump Systems

- ▶ The objective of the **heat pump** is to **maintain** the **temperature of a space** or **industrial process** above the **temperature of the surroundings**.
- ▶ **Principal control volumes** involve these components:
 - ▶ Evaporator
 - ▶ Compressor
 - ▶ Condenser
 - ▶ Expansion valve



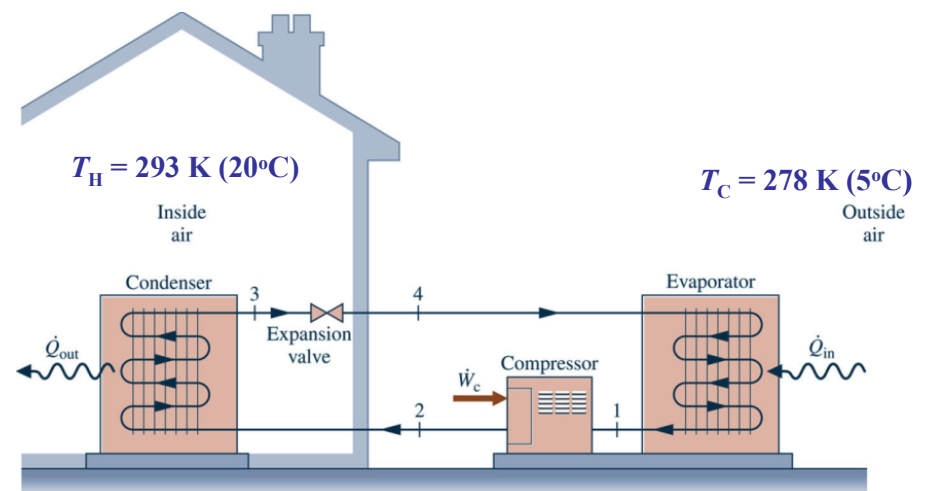
Vapor-Compression Heat Pump System

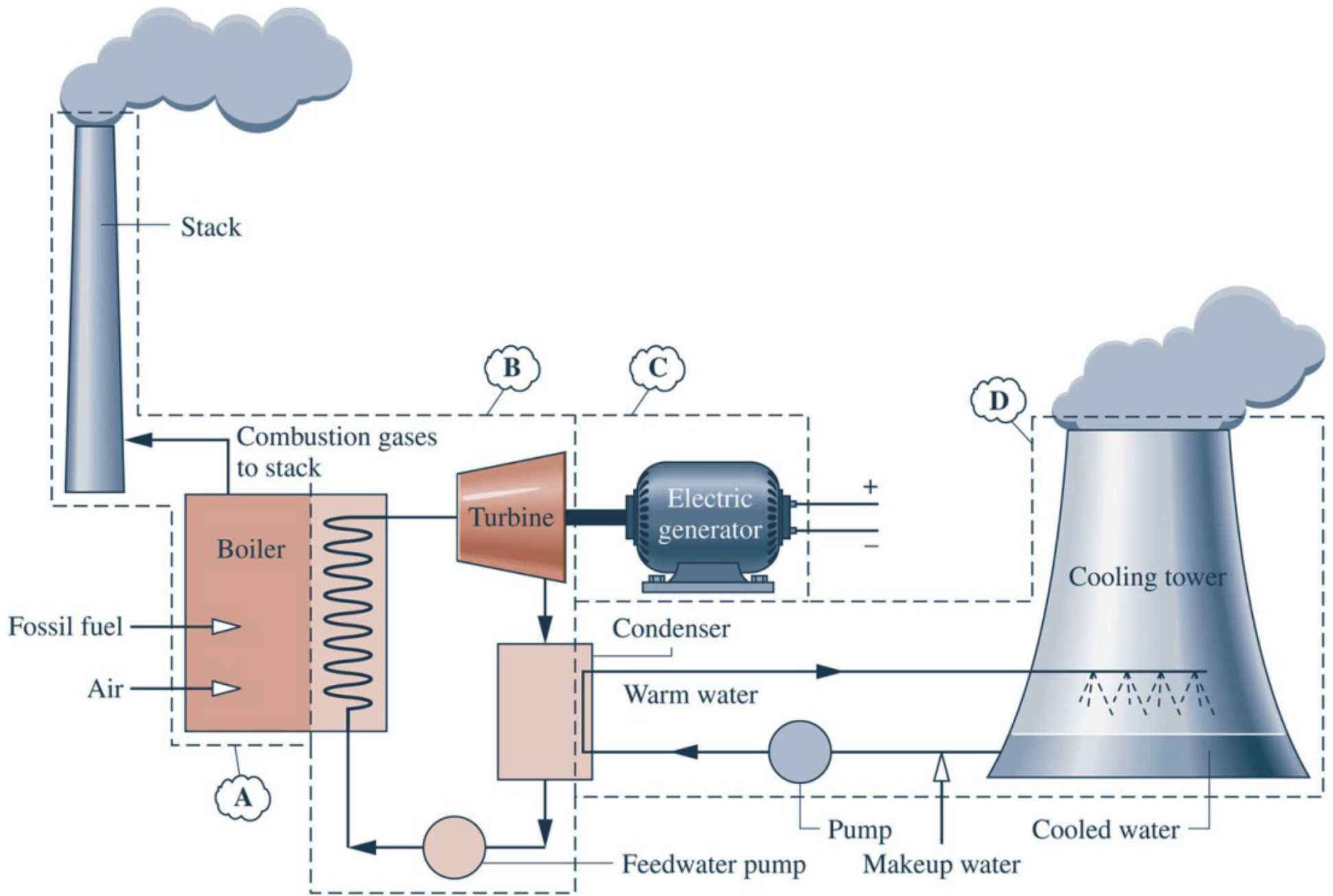
► The **method of analysis** for vapor-compression heat pumps closely parallels that for vapor-compression refrigeration systems.

Example: A vapor-compression heat pump cycle with R-134a as the working fluid maintains a building at 20°C when the outside temperature is 5°C . The refrigerant mass flow rate is 0.086 kg/s . Additional steady state operating data are provided in the table. Determine the

- (a) compressor power, in kW,
- (b) heat transfer rate provided to the building, in kW,
- (c) coefficient of performance.

State	1	2	3
h (kJ/kg)	244.1	272.0	93.4

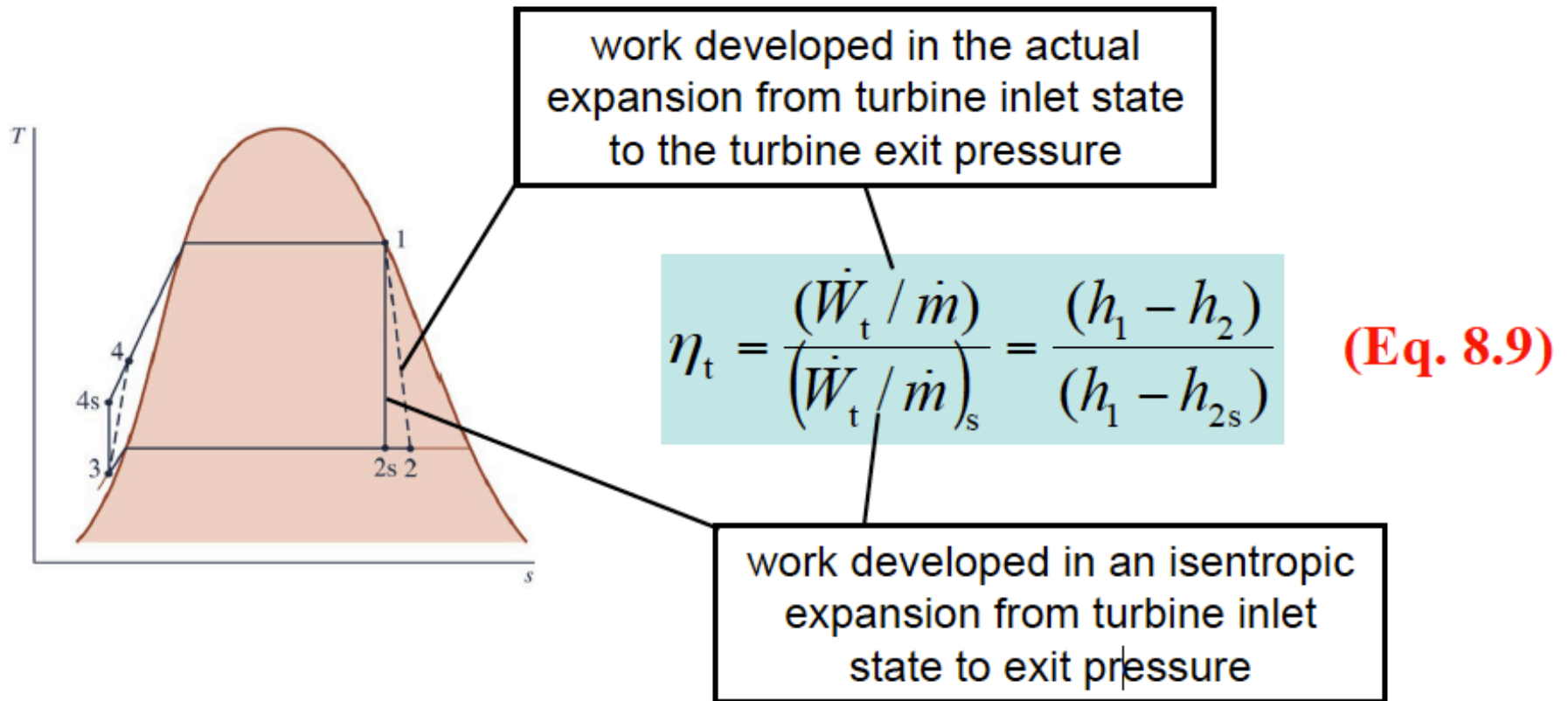




(a) Fossil-fueled vapor power plant.

Principal Irreversibilities

► **Isentropic turbine efficiency**, introduced in **Sec. 6.12.1**, accounts for the effects of irreversibilities within the turbine in terms of actual and isentropic turbine work, each per unit of mass flowing through the turbine.



Principal Irreversibilities

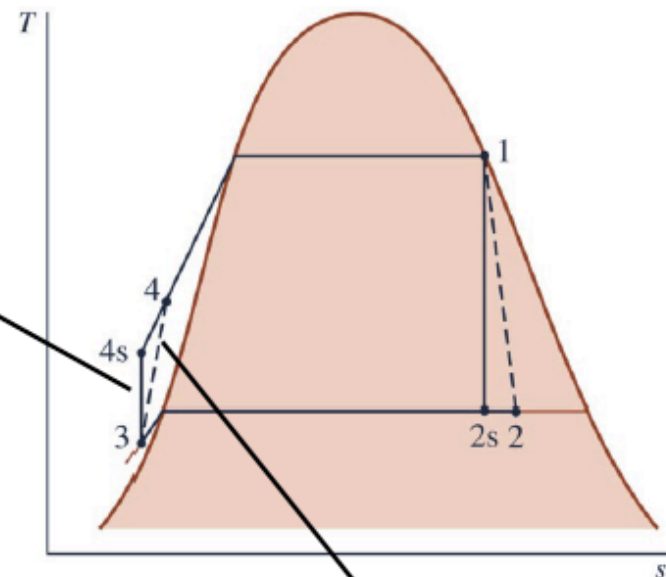
► While pump work input is much less than turbine work output, **irreversibilities in the pump affect net power output** of the vapor plant.

► **Isentropic pump efficiency**, introduced in **Sec. 6.12.3**, accounts for the effects of irreversibilities within the pump in terms of actual and isentropic pump work input, each per unit of mass flowing through the pump.

work input for an isentropic process from pump inlet state to exit pressure

$$\eta_p = \frac{(\dot{W}_p / \dot{m})_s}{(\dot{W}_p / \dot{m})} = \frac{(h_{4s} - h_3)}{(h_4 - h_3)} \quad \text{(Eq. 8.10a)}$$

work input for the actual process from pump inlet state to the pump exit pressure



I hope you've enjoyed the course,
(or at least the M&Ms)

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They are important.

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Thermodynamics

Use "X" (not checks, or blocks)
Use Blue or Black Pen